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Ionizing Photons and EUV Excesses in Clusters of Galaxies

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ABSTRACT

Observations with the *Extreme Ultraviolet Explorer* satellite are purported to show extreme ultraviolet (EUV) and soft X-ray excesses in several clusters of galaxies (Bonomonte, Lieu & Mittaz 2001). If interpreted as thermal emission, this would imply the presence of warm ($T \sim 10^6$ K) gas in these clusters with a mass comparable to that of gas at coronal temperatures. If true, this would have profound implications for our understanding of galaxy clusters and the distribution of baryons in the universe. Here we show that because of the large ionizing photon emissivities of gas at such low temperatures, the ionizing photon fluxes seen by disk galaxies in the observed clusters can be very large, resulting in minimum emission measures from neutral gas in such disks as high as $100 \text{ cm}^{-6} \text{ pc}$. This result is essentially independent of the mechanism actually responsible for producing the alleged EUV excesses. The predicted emission measures in Abell 1795 ($z = 0.063$) are about an order of magnitude larger than seen in the Reynolds layer of the Galaxy, providing a straightforward observational test of the reality of the EUV excess. New tunable filter $\text{H}\alpha$ images and WFPC images from the Hubble Space Telescope archive do not support the existence of the claimed EUV excess.

Subject headings: galaxies: clusters: general – galaxies: clusters: individual (Abell 1795, Virgo) – ultraviolet: galaxies

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1. Introduction

Rich clusters of galaxies are one of the major identified reservoirs of baryons at low redshift; the contribution of hot plasma in clusters to Ω_{baryon} is comparable to that of the stellar components of galaxies (Fukugita, Hogan & Peebles 1998). Most of the intracluster medium (ICM) in galaxy clusters is at temperatures $T \sim 1 - 10$ keV, as expected from the depth of the potential wells traced by the galaxies, although the high-density cores of clusters may exhibit gas at lower temperatures (*e.g.*, Sarazin 1988). This hot gas radiates primarily through thermal bremsstrahlung. Since bremsstrahlung is intrinsically broad-band emission, the ICM should be detectable at soft X-ray and extreme ultraviolet (EUV) wavelengths as well as keV energies.

The *Extreme Ultraviolet Explorer* (*EUVE*) satellite provided the capability to observe at energies of order 100 eV; the precise bandpass depends on convolution of the instrument response with the absorption due to the intervening interstellar medium. *EUVE* observations of several clusters of galaxies have been interpreted as implying substantial EUV emission in excess of that expected from the gas observed at keV energies (Lieu *et al.* 1996a,b; Mittaz, Lieu & Lockman 1998). This claim has been disputed by Bowyer, Berghöfer & Korpela (1999) who argue that the EUV excesses are an artifact caused by improper subtraction of the instrumental background (although they infer that the relatively weak EUV excesses in the Virgo and Coma clusters may be real), and an increasingly fractious debate has ensued (*e.g.*, Lieu *et al.* 1999; Bonamente, Lieu & Mittaz 2001, hereafter BLM; Berghöfer, Bowyer, & Korpela 2000; Bonamente *et al.* 2001). Dixon, Hurwitz, & Ferguson (1996) and Dixon *et al.* (2001) used the *Hopkins Ultraviolet Telescope* (HUT) and *Far-Ultraviolet Spectroscopic Explorer* (FUSE), respectively, to search for the far-UV resonance lines of C IV $\lambda\lambda 1548, 1551$ and O VI $\lambda\lambda 1032, 1036$ (both the carbon and oxygen lines in the former paper and just the oxygen lines in the latter), which would be expected to be prominent if the EUV excesses are produced by warm gas. Neither observation detected any line emission; Dixon *et al.*, in particular, ruled out the existing warm gas models for the Virgo and Coma clusters at the 2σ level. In this *Letter*, we present an alternative probe of the reality of the EUV excesses, namely, observations of recombination line radiation produced by irradiation of neutral gas in galaxies by the ionizing radiation associated with the EUV excesses.

2. Cluster Ionizing Photon Fluxes

Two different mechanisms have been proposed to explain the EUV excesses: thermal emission from warm ($T \sim 10^6$ K) gas (Lieu *et al.* 1996a), and inverse Compton (IC) scattering of cosmic microwave background photons by nonthermal electrons in the cluster (Hwang 1997; Ensslin & Biermann 1998). Both of these mechanisms suffer from serious difficulties. In the thermal model, the gas cooling times are so short that it is difficult to see how such emission could be sustained for more than a small fraction of the age of the cluster. Fabian (1997) proposed that the EUV emission arises in mixing layers, so that the energy source for the emission is the thermal reservoir of hot gas.

This could alleviate the cooling difficulty for several of the clusters but probably fails for the most EUV-luminous cluster, Abell 1795 (A1795). The nonthermal model sidesteps this problem; however, it runs into difficulties with the strength of cluster magnetic fields (*e.g.*, Kempner & Sarazin 2000) and the pressure of nonthermal particles (including the relativistic electrons) (Bowyer & Berghöfer 1998; BLM).

We adopt the thermal interpretation of the EUV excesses since BLM have presented detailed thermal fits (gas density and temperature) as a function of radius to the EUV emission from the Virgo and A1795 clusters. As these fits by definition reproduce the alleged EUV excesses in these clusters, the resulting ionizing photon fluxes ϕ_i should not be very sensitive to this choice as opposed to an IC model. (Since the emission from a power-law electron distribution will have a broader energy distribution than thermal emission, which is dominated by line emission at these temperatures, a thermal model will produce smaller values of ϕ_i than an IC model.)

For simplicity, we assume a spherically symmetric distribution of gas; because of the integration over angle and radius, we expect the results to be insensitive to this assumption. Specifically, we take the radial distribution of protons to be described by a β -model,

$$n(r) = n_o [1 + (r/r_o)^2]^{-3\beta/2} \quad (1)$$

where n_o and r_o are the core density and radius, respectively. Assuming thermal emission from the gas, the ionizing photon emissivity is proportional to n^2 , and the normally incident ionizing photon flux on a surface at radius R oriented normally to the radius vector is given by

$$\phi_i = 2\pi\xi_i n_o^2 r_o^6 x_o^{6\beta-1} \int_{\theta_{\min}}^{\theta_{\max}} \int_0^{x_m} d\theta dx \sin\theta \cos\theta A_x^{-3\beta} \quad \text{phot cm}^{-2} \text{ s}^{-1} \quad (2)$$

where $x = r/R$, $x_o = r_o/R$, and $A_x \equiv 1 + x_o^2 + x^2 - 2x \cos\theta$. The ionizing photon emissivity ξ_i is defined so that $n^2\xi_i$ is the number of ionizing photons emitted $\text{cm}^{-3} \text{ s}^{-1} \text{ sr}^{-1}$. The integral over the radial variable can be done analytically for 3β equal to an integer or half-integer. The limits of the angular integration depend on the hemisphere of integration; $(\theta_{\min}, \theta_{\max}) = (0, \pi/2)$ gives the flux on the inward-facing surface, while $(\pi/2, \pi)$ gives the flux on the outward surface. The maximum radius of integration x_m is θ -dependent for a finite gas distribution.

For consistency with the thermal fits in BLM, we have used the the MEKAL plasma code (Kaastra, Mewe, & Nieuwenhuijzen 1996, as implemented in the SPEX software package: Kaastra *et al.* 1995) to calculate the ionizing photon emissivities for the cluster gas. In figure 1 we plot ξ_i as a function of the gas temperature; we have taken the upper limit to be 500 eV in calculating ξ_i , but the results are insensitive to this assumption. Metal abundances of 1/3 solar have been assumed. For comparison, we have also plotted ξ_i as calculated using the MAPPINGS III code (Sutherland & Dopita 1993; Dopita & Sutherland 1996). The largest differences are about 40%, which we take to be a measure of the uncertainty in the predicted ϕ_i .

In Figure 2 we plot the normally incident photon flux ϕ_i on a surface as a function of radius for the A1795 cluster. (This is the sum of the fluxes incident on opposite sides of the surface.)

The upper solid curve uses the thermal fit to the EUV emission from BLM. Because this result is sensitive to the density at the largest radius for which BLM present results, we have also plotted ϕ_i for this model with the gas density in the outermost bin reduced by its stated uncertainty (dashed line). Finally, the lower solid curve shows the ionizing photon flux expected from the hot X-ray-emitting gas in the cluster, with the T and n as derived from XMM-Newton observations (Tamura *et al.* 2001)³. Although, as noted above, the curves are for a surface oriented normally to the radius vector, the extremely weak dependence on radius for the models with EUV excesses indicates that the actual fluxes incident on galactic disks at random orientations within the cluster will not differ significantly from the plotted values.

3. Discussion

From the plot of ionizing photon fluxes in Figure 2, we see that ϕ_i will be a minimum of one to two orders of magnitude larger if the EUV excess claimed in A1795 by BLM is present than it would be if there is only the more conventional hot gas component; over most of the cluster volume, the ratio is actually much larger, $\sim 10^2 - 10^3$, since ϕ_i from the EUV component is much less centrally concentrated than the hot gas. Any spiral galaxy within the inner $10'$ ($660h_{70}^{-1}$ kpc at the distance of A1795) will see an ionizing photon flux $\phi \approx 5 \times 10^7$ phot cm⁻² s⁻¹ (for the warm gas parameters derived by BLM). The corresponding emission measure (normal to the disk) $\mathcal{E}_m \approx 63$ cm⁻⁶ pc, assuming $T_e \approx 10^4$ K (*e.g.*, Maloney & Bland-Hawthorn 1999). For comparison, this is about ten times larger than the emission measure characterizing the warm ionized medium (the Reynolds layer: Reynolds 1984).

This offers a straightforward observational test of the reality of the EUV excesses. The large predicted emission measures can be easily probed through recombination line observations. In particular, the predicted H α surface brightness is

$$I_{\text{H}\alpha} = 35.7 \left(\frac{\mathcal{E}_m}{100 \text{ cm}^{-6} \text{ pc}} \right) \text{ Rayleigh} \quad (3)$$

where $1 \text{ Rayleigh} = 10^6/4\pi \text{ phot cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, and we have normalized to the expected \mathcal{E}_m for galaxies in A1795⁴. The resulting $I_{\text{H}\alpha}$ depends only on ϕ_i and is independent of T_e and n . Emission measures as low as unity can be reached quite readily with a differential narrow-band

³Since we actually truncate the cluster gas distribution at $10'$ radius, the limit of the fits presented by BLM, the curves in Figure 2 are lower limits to the true ionizing fluxes; this effect is much more important for the EUV excess models.

⁴We have performed similar calculations for the Virgo cluster, for which BLM also present detailed fits, but we do not present them as the results are uninteresting: the EUV excess contribution does not exceed that from the hot gas in the cluster (which has $T_{\text{kev}} \sim 1$), and the ionizing photon flux drops below the cosmic background level at a distance smaller than the separation of any disk galaxy from the center of the emission. This is largely a consequence of the small spatial scale of the emission, which is concentrated on the giant elliptical galaxy M87.

imager, in particular, the TAURUS Tunable Filter⁵ (TTF) which combines beam switching and frequency switching to suppress atmospheric variability (Bland-Hawthorn & Jones 1998). These faint emission levels can also be reached in one night with spectrographs on 8m class telescopes (Cirkovic, Bland-Hawthorn, & Samurovic 1999).

The cluster-induced H α emission can be easily distinguished from the warm ionized media intrinsic to the cluster galaxies, even if we adopt a reduced density in the outer regions of the cluster (dashed curve in Figure 2). The surface brightness of the diffuse ionized gas in spiral disks are typically of the same order as in the Reynolds layer, with $\mathcal{E}_m \sim 10 \text{ cm}^{-6} \text{ pc}$ (*e.g.*, Ferguson *et al.* 1996; Hoopes, Walterbos, & Greenawalt 1996; Greenawalt, Walterbos, & Braun 1997; Greenawalt *et al.* 1998), and decline with increasing radius, generally to $\mathcal{E}_m \sim 1 \text{ cm}^{-6} \text{ pc}$ around the edge of the optical disk. The radial behavior of the cluster-induced H α will be very different. Since the cluster ionizing field will be uniform across a galactic disk, the entire neutral hydrogen disk of a galaxy, even outside the optical disk, should be glowing in H α at the same level. Hence this component will be flat with radius, and extend outside of the optical disk, as far as the neutral hydrogen edge. We also note that even such high ionizing photon fluxes probably do not significantly increase the critical column density for ionization of galactic neutral hydrogen disks above the value expected in field spirals due to the cosmic ionizing background (Maloney 1993), since the pressure of the ICM will force the ISM of cluster spirals to high values ($P/k \gtrsim 10^4 \text{ cm}^{-3} \text{ K}$) even at large radius.

This technique would fail if stripping of gas from spiral galaxies in the cluster were a very efficient process, as suggested by early HI observations of the densest clusters (Giovanelli & Haynes 1985; Cayette *et al.* 1990). However, more recent studies show that stripping is less effective than originally suggested. The most comprehensive survey to date, incorporating 1900 galaxies in 18 clusters (Solanes *et al.* 2001), finds that more than one-half of spirals retain at least half their HI within $\sim 900 h_{70}^{-1} \text{ kpc}$ ($13'$ at the distance of A1795). This is the scale, roughly 40% of an Abell radius, over which we expect to see disks with bright H-alpha disks or halos (see Fig. 2). A third of the clusters in the Solanes *et al.* sample show no H I deficiency.

We have investigated the brighter end of the predicted range of ϕ_i using archival broad-band images of the core of A1795. An emission measure of \mathcal{E}_m produces an R band surface brightness of $\mu_R \approx 31.5 - 2.5 \log \mathcal{E}_m \text{ mag arcsec}^{-2}$. An extended HI disk seen face-on glowing at $\mathcal{E}_m \approx 100 \text{ cm}^{-6} \text{ pc}$ corresponds to $\mu_R \approx 26.5$; this rises to $\mu_R \approx 25$ for a disk viewed edge on. We have reanalyzed the *Hubble Space Telescope* (HST) WFPC2 images of A1795 obtained by J. Trauger (ID 5212) (*q.v.*, McNamara *et al.* 1996). The flux-calibrated F702W images have a summed exposure time of 1780 sec. The combined image achieves $\mu_R \approx 25 \text{ mag arcsec}^{-2}$ at S/N ≈ 0.5 per WFPC pixel. When smoothed over $1''$, we see no evidence of faint, flat H α halos down to $\mu_R \approx 26.5$ (2σ). The disk galaxies appear to be exponential down to and below this level. (The HST has been used to reach down to $28 \text{ mag arcsec}^{-2}$ in broadband images, *e.g.*, Tyson *et al.* 1998. At these levels, it would be possible to detect H α halos with $\mathcal{E}_m \approx 10 \text{ cm}^{-6} \text{ pc}$ in inclined galaxies.) However, the WFPC2

⁵See the TTF web site at <http://www.aao.gov.au/ttf/>

L-shaped field of view is only about $3'$.

We have attempted a second experiment with the TTF at the Anglo-Australian Telescope (AAT) in order to reach fainter levels in $H\alpha$ over a $10'$ diameter field. A1795 was observed for us by A. Edge and K. Baker on 2001 Mar 3 using the TTF at the AAT f/8 Cassegrain focus. The tunable filter was set to 14\AA effective bandpass. To suppress systematic errors induced by the atmosphere, we used the TTF in ‘straddle shuffle’ mode. The on band exposures (6970\AA) were interleaved with blue and red off band exposures ($6920\text{\AA}, 7050\text{\AA}$). This differential imaging mode produces perfect off-band subtraction (zero systematic error) not possible with conventional imaging filters (Bland-Hawthorn & Jones 1998). Two observing sequences gave a total exposure time of 20 minutes each on the redshifted $H\alpha$ line and the summed off band (Figure 3).

While the photometric conditions were good, the seeing was variable around $1.6''$. The flux-calibrated data reach a surface brightness $E_m \approx 5 \text{ cm}^{-6} \text{ pc}$ at 2σ . *At these faint levels we find no evidence of diffuse $H\alpha$ disks or extended $H\alpha$ halos for galaxies over the $10'$ field.* There is evidence for nucleated star formation in some galaxies, and the central dominant elliptical shows evidence of a spectacular cooling flow (Edge *et al.* 2001, in preparation).

The preliminary observations from HST and the TTF do not support the existence of faint extended halos or disks within $5'$ ($350h_{70}^{-1} \text{ kpc}$) of the cluster core.

4. Summary

We present an independent method for determining the reality of the alleged EUV excesses in galaxy clusters. At least for the case of Abell 1795, the ionizing photon fluxes implied by the claimed EUV emission imply that the neutral hydrogen disks of spiral galaxies within the cluster (out to at least $10'$ radius from the cluster center, corresponding to about 660 kpc) should be glowing in hydrogen recombination lines, with surface brightnesses of tens of Rayleighs at $H\alpha$. Current instrumental sensitivities should make it possible to detect the $H\alpha$ emission expected due to the ionizing photon flux from the hot gas in the cluster (which is two orders of magnitude or more weaker than the predicted fluxes in the EUV excess model) out to several arcminutes radius, and hence $H\alpha$ observations can easily discriminate between the two cases and provide stringent limits on the presence of any additional source of ionization for spiral galaxies within the cluster. A preliminary investigation using archival broad-band images and new $H\alpha$ observations does not support the existence of the alleged EUV excess in this cluster.

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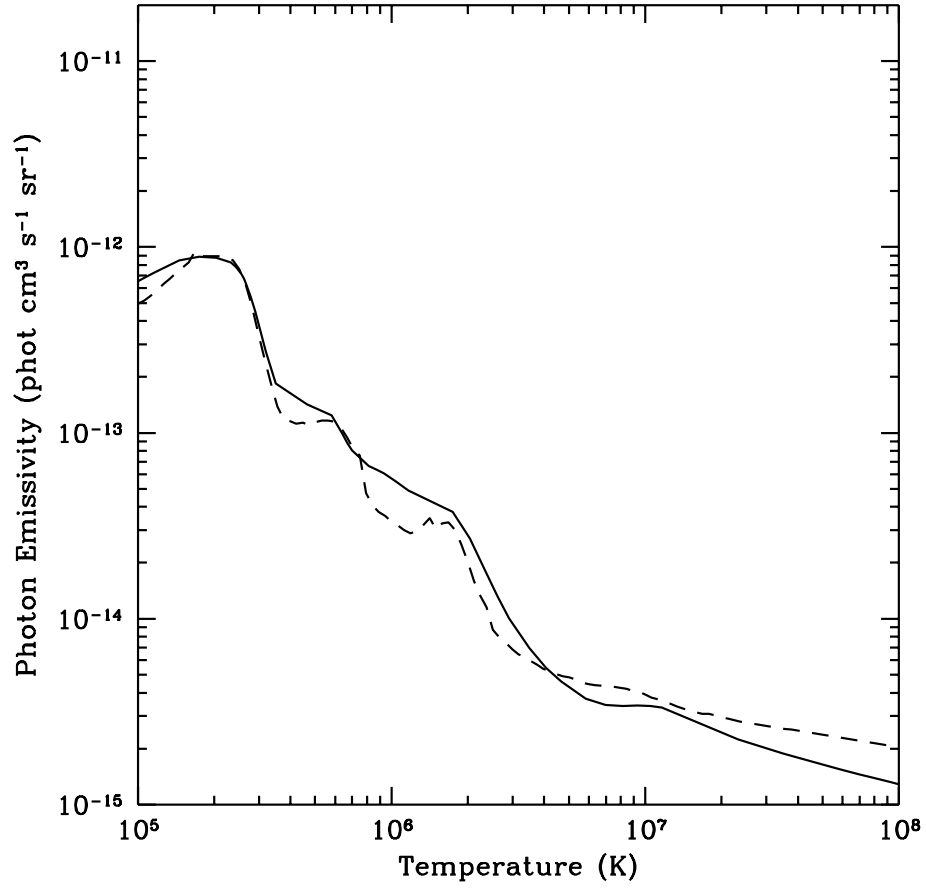


Fig. 1.— Ionizing (13.6 – 500 eV) photon emissivity ξ_i (phot cm³ s⁻¹ sr⁻¹) as a function of gas temperature, as calculated with MEKAL (solid line) and MAPPINGS III (dashed line).

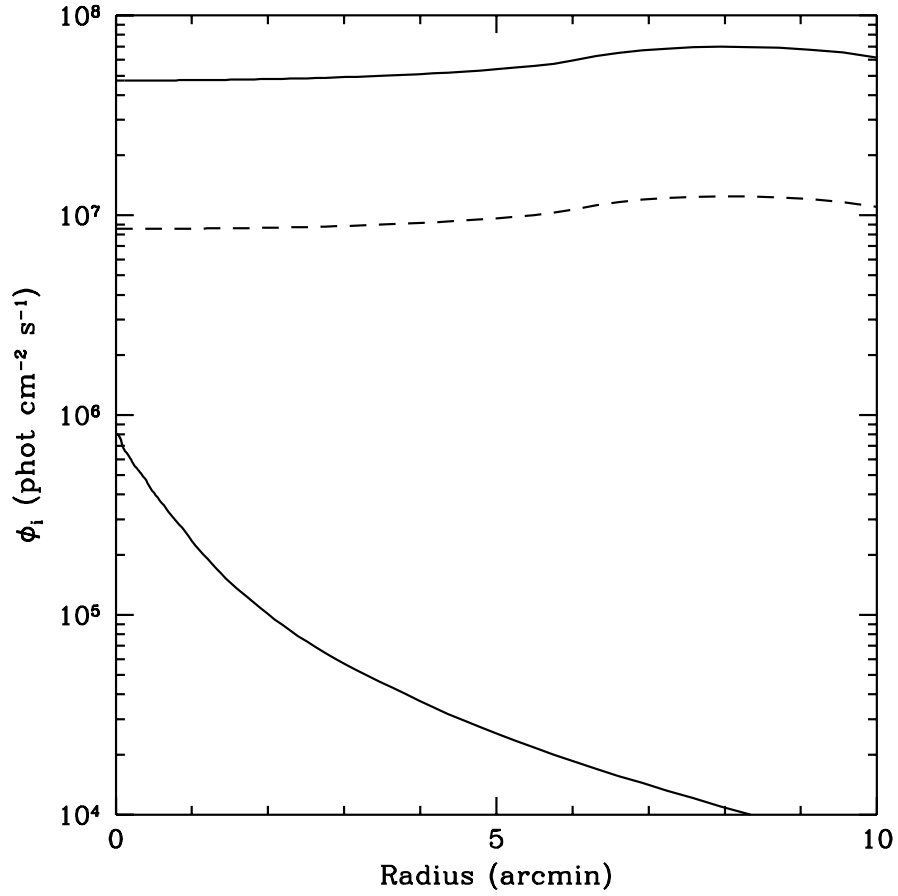


Fig. 2.— Normally incident ionizing photon fluxes ϕ_i as a function of radius in the A1795 cluster, as derived from thermal fits to the EUV excess claimed by BLM (upper solid line) and from fits to the X-ray emission observed with XMM-Newton (Tamura *et al.* 2001) (lower line). The dashed curve shows ϕ_i for the EUV excess fit with the density in the outermost bin reduced by its stated uncertainty. Only the contribution from gas within 10' of the cluster center has been included.

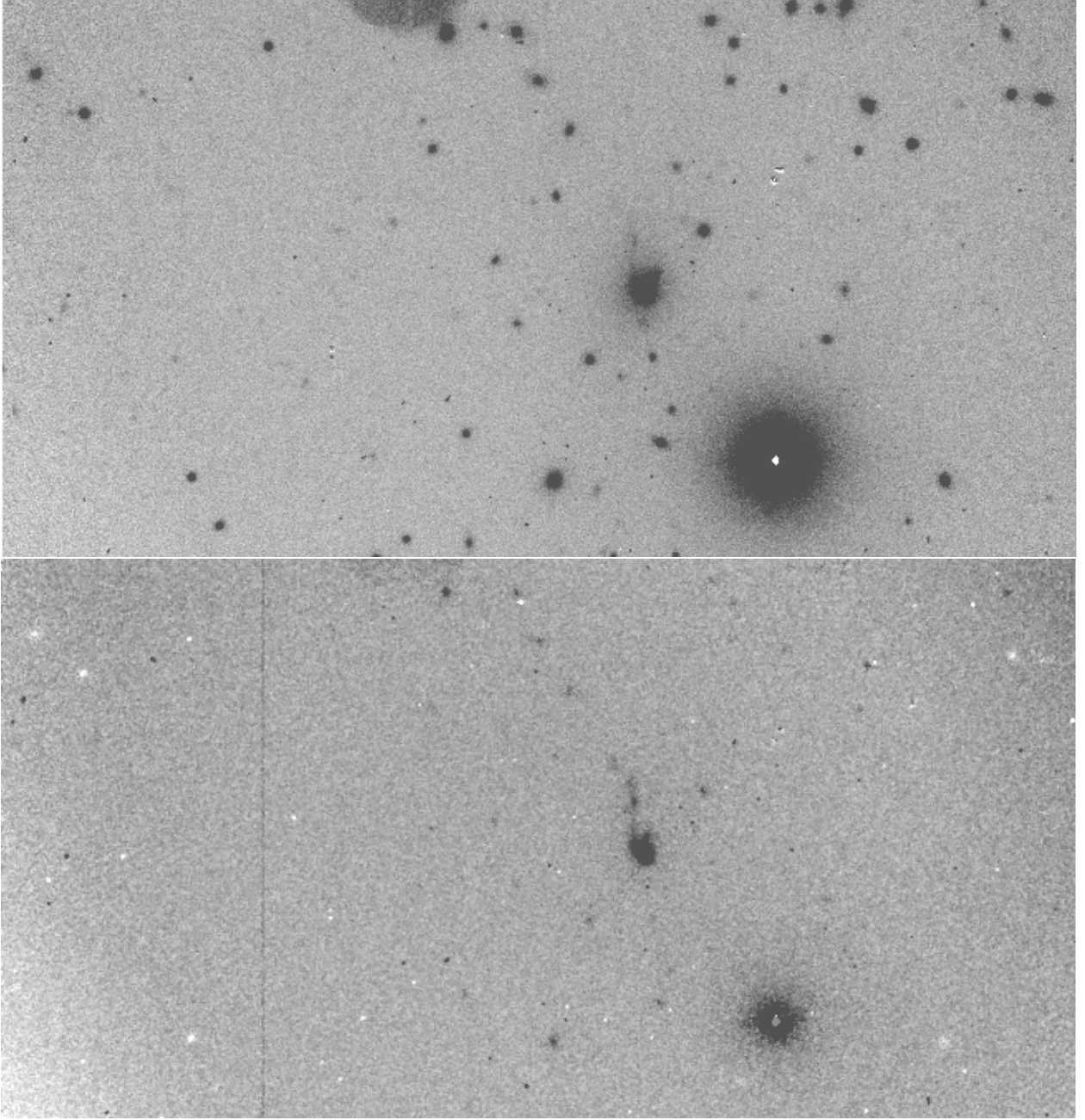


Fig. 3.— Sections of the TTF ‘straddle shuffle’ image of A1795 showing $H\alpha$ emission at the cluster redshift ($z = 0.063$). The upper strip is the sum of the on and off bands. (The half annulus is an out-of-focus ghost of the bright star to the SW.) The lower strip is the continuum-subtracted line band. The field of view for each strip is $4.2'$ by $8.0'$. Galaxies show either weak Balmer absorption or nucleated $H\alpha$ emission. The central giant elliptical has a spectacular cooling flow with $H\alpha$ filaments characterized by $E_m = 5 - 100 \text{ cm}^{-6} \text{ pc}$.